Recent Improvements to Selenochronology by Samples and Missions and Models

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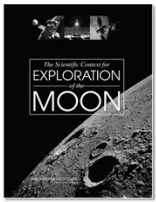
High-priority lunar science goals



1a. Test the cataclysm hypothesis by determining the spacing in time of the creation of the lunar basins.
1b. Anchor the early Earth-Moon impact flux curve by determining the age of the oldest lunar basin (South Pole-Aitken Basin).
1c. Establish a precise absolute chronology.
4a. Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and depth) of the volatile component in lunar polar regions.
3a. Determine the lateral extent and composition of the primary feldspathic crust, KREEP layer, and other products of planetary differentiation.
2a. Determine the thickness of the lunar crust (upper and lower) and characterize its lateral variability on regional and global scales.
2b. Characterize the chemical/physical stratification in the mantle, particularly the nature of the putative 500-km discontinuity and the composition of the lower mantle.
8a. Determine the global density, composition, and time variability of the fragile lunar atmosphere before it is perturbed by further human activity.
2c. Determine the size, composition, and state (solid/liquid) of the core of the Moon.
3b. Inventory the variety, age, distribution, and origin of lunar rock types.
8b. Determine the size, charge, and spatial distribution of electrostatically transported dust grains and assess their likely effects on lunar exploration and lunar-based astronomy.

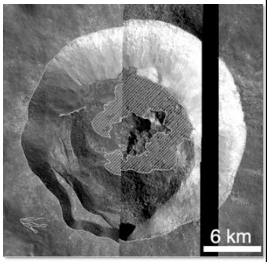
Importance of impact craters

- LRO Targeting Workshop (2009) - How LRO can help address issues in impact cratering
- The Moon is a lab for understanding the impact process
  - Craters are preserved better than on any other planet
  - Craters are numerous and range over size and terrain
  - The Moon is airless and volatile free, so some variables are simpler
- The Moon preserves a temporal record of the Earth-Moon bombardment flux
  - Relative crater densities can be tied to absolute sample ages
  - Stratigraphic relationships can be recognized
- Craters will be targets for future robotic and human exploration

- **What progress has been made since then?**

Origin of impact-melt rocks

- Lunar Reconnaissance Orbiter Camera (LROC) and Mini-RF radar images reveal that impact melt deposits have complex morphologies on m- to km- scales (Bray et al., 2010; Carter et al., 2010; Robinson et al., 2010)
- New LROC WAC images show that the Sculptured Hills (A17 poikilitic impact-melt rocks) are not localized around the Apollo 17 site, but are widespread throughout the Taurus Mountains – are these rocks Serenitatis or Imbrium? (Spudis et al. 2011)



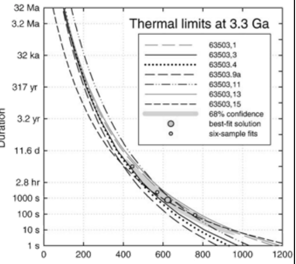
Melt distribution map of lunar crater Moore F. Impact melt units include: hummocky floor melt (pink stripes) to the NE, smooth melt ponds (magenta), and channeled melt flows (orange). From Bray et al. (2010).

New sample ages

- Pre-3.9 Ga ages of non-impact-melt samples
  - Apollo 16 and 17 granulitic breccias have peak metamorphic ages of 3.9 Ga OR 4.1 Ga (Hudgins et al. 2008)
  - A14 and A17 zircon overgrowths are 4.33 and 4.2 Ga (Grange et al. 2009, 2011)
  - Seven Apollo 16 regolith samples (feldspathic breccias and anorthosites) have plateau ages 3.9 Ga OR 4.2 Ga (Shuster et al. 2010)
  - Unique mafic-mineral rich sample of FAN 60025 has a multiple-isotopic age of 4360 ± 3 Ma (Borg et al. 2011)
- Are these recording ancient basin-forming impact events or lunar igneous activity?

Additional insight from samples

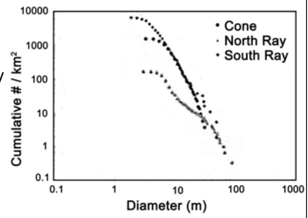
- A16 anorthosites experienced partial loss by a heating event 3.3 Ga, likely an additional impact event (Shuster et al. 2010)
- Basaltic meteorites crystallized 3.7-3.8 Ga but show partial loss corresponding to impact event ~200 and ~600 Myr ago (Fernandes et al. 2010)
- Polycrystalline zircon in lunar meteorite Dhofar 458 recrystallized at 3.4 Ga (Zhang et al. 2011)



Duration–temperature constraints on a thermal excursion experienced by 63503 at 3.3 Ga derived from seven samples in regolith sample 63503 (Shuster et al. 2010).

New crater counts

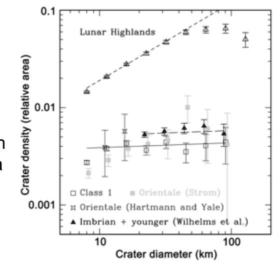
- New crater counts to small sizes using LROC & LO images indicate that lunar surfaces have more secondary craters than previously anticipated (Hiesinger et al. 2010, Kirchoff et al. 2010, Plescia and Robinson 2011)
- New small crater frequencies give model ages greater than the known radiometric age
- The calibration between absolute age and crater frequency for young ages has significant uncertainties



Cumulative crater size-frequency data for ejecta surfaces of Cone, North Ray and South Ray craters from LROC images (Plescia and Robinson 2011).

Old crater counts, revisited

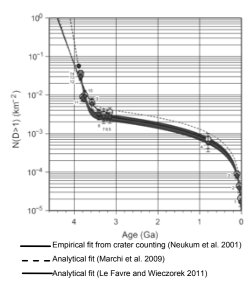
- Lunar highlands have SFD similar to main belt asteroids, while “morphologically fresh” Class 1 craters have SFD similar to NEAs (Strom et al. 2005)
- Cuk et al. (2010) argue that Class 1 craters have the same density on the whole moon as on basin ejecta blankets – therefore must be remnants of the LHB
- How can crater counts from different units be combined? Does crater morphology correlate with age? How are secondaries accounted for?



Size-frequency distributions of different crater classes (Cuk et al. 2010)

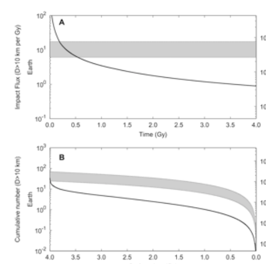
Lunar crater chronology calibration curves

- New lunar crater production functions derived from impact modeling differ significantly from those based on measurements (Marchi et al. 2009, Le Fevre and Wieczorek 2011)
  - reconcile measured lunar SFD with near-Earth asteroid population by assuming craters < few km form in a porous megaregolith, suggested by Ivanov et al. (2007)
  - quantify spatial cratering asymmetries that may bias crater density ages – worse for smaller bodies than larger
  - Estimate both Orientale and Caloris basins to be 3.73 Ga



Dynamical evolution of the source

- Dynamical modeling of larger main belt asteroids shows that these are subject to loss; predicted rate of impacts declines by a factor of 3 over the last 3 Gyr (Minton and Malhotra 2010)
- “E-belt” source of main-belt asteroids predicts production of large lunar basins, long tailoff at Earth, and later siderophile veneer (Bottke et al. 2010, 2011)



Impact rates of D > 10 km asteroids on the Earth and Moon from model of Minton and Malhotra (2010) compared with the Neukum Production Function (shaded regions).

Terrestrial record

- Terrestrial spherule beds continue to be discovered: 3.47-3.23 Ga (7) 2.63-2.49 Ga (4) 2.1-1.6 Ga (2) (Glikson 2010)
- Isua metasedimentary rocks are enriched (150 ppt) in iridium compared to present-day ocean crust (20 ppt) – argues to be evidence of cometary input rather than asteroidal (Jørgensen et al. 2009)
- New (U, Th)-He technique for terrestrial impact-generated zircons (van Soest et al. 2010, Wartho et al. 2011)

Conclusions

- Selenochronology is getting more complicated: new results question meaning of sample ages, crater counts, crater production functions, and the solar system itself
- But there is hope!
  - Improved geological mapping of lunar geologic units and boundaries using multiple remotes-sensing datasets
  - High-resolution image-based crater counting of discrete geologic units and relating them to location
  - Improved understanding of the regolith thickness and its global variation (GRAIL)
  - Tying the sampling of impact-melt rocks to the lunar impact flux
  - Using improved techniques (magnetic fields, diffusion studies, isotopic analysis) on existing samples
  - New sample return from benchmark craters, particularly SPA, which appears in 2013 Decadal Survey